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Realization of 520 nm Green Laser Diodes with InGaN/AlGaN/GaN Multiple Quantum Well Active Region

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Abstract: Green laser diodes(LDs) suffer from the well-known "green gap" problem, characterized by low wall plug efficiency in the green spectral region. This is mainly attributed to the difficulty in achieving high-quality active regions. In this work, we designed and grew a novel active region with an InGaN/AlGaN/GaN multiple quantum wells (MQWs) structure. Owing to the protective effect of AlGaN, the surface morphology of the MQWs was greatly improved, a yellow- emitting MQW with a root-mean-square(RMS) roughness as low as 0.5 nm has been achieved. Finally, we fabricated InGaN/AlGaN/GaN MQW green laser diodes(LDs) with a wavelength of 520 nm. The LD exhibited a slope efficiency of 0.36 W/A and an optical output power of 180 mW at 2 A.

Keywords: MOCVD; GaN; LD; AlGaN cap

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基于InGaN/AlGaN/GaN量子阱有源区的520 nm绿光激光二极管

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摘要:绿光激光二极管存在"绿光鸿沟"问题,即绿光范围内器件的光电转换效率较低,其主要原因是难制备高质量的量子阱有源区。本文设计并生长了一种新型InGaN/AlGaN/GaN量子阱有源区结构,由于AlGaN盖层的保护作用,多量子阱表面形貌得到明显改善,成功制备出均方根粗糙度低至0.5 nm的黄光多量子阱有源区。基于该有源区制备出激射波长为520 nm的InGaN/AlGaN/GaN量子阱绿光激光二极管,在2 A的电流下,斜效率可达0.36 W/A,输出光功率达180 mW。

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关 键 词：MOCVD；GaN；激光二极管；AlGaN盖层

1 Introduction

GaN-based laser diodes (LDs) have extensive applications in fields such as laser display and visible-light communication[1-6], owing to their advantages of small size, long lifetime, and excellent monochromaticity. However, the performance of green LDs is still unable to meet the requirements of certain applications because the performance of green LDs degrades significantly as the wavelength increases[7], which severely limits the development of full-color display and visible-light communication.

In 1995, Nakamura et al. fabricated the first GaN-based LDs with a lasing wavelength of 417 nm[8]. The development of green LDs started relatively late. It was not until 2009 that Osram successfully realized GaN-based green LDs with a lasing wavelength up to 500 nm. The threshold current density of was 8.2 kA/cm^2, and its optical output power reached up to several tens of milliwatts[9]. In recent years, the performance of green LDs has been greatly enhanced. In 2024, Nichia demonstrated green LDs with a lasing wavelength of 525 nm. The WPE and optical output power of the green LD were 24.2% and 1.90 W at the CW current of 1.9 A, respectively[10]. In 2026, ams-OSRAM presented a series of green LDs covering the wavelength range of 515-538 nm. At room temperature and 2 A, these devices achieve an optical output power exceeding 1.9 W and a power conversion efficiency above 24%[11].

Active region is the core structure of LDs, which exerts a decisive influence on device performance. Improving the quantum efficiency of active region of green LDs has the following difficulties: (1) the QWs need to have a high indium composition exceeding 30%. The lattice mismatch between $In_{0.3}Ga_{0.7}N$ QW and GaN quantum barrier (QB) is as high as 3.2%, which is easy to produce mismatch dislocations. The large compressive stress in the QW hinders indium incorporation and induces phase separation[12]. (2) A high polarization electric field induces a strong Quantum Confined Stark effect (QCSE), leading to reduced luminescence efficiency and a redshift of the emission peak[13-14]. Therefore, the wavelength difference between spontaneous emission and lasing must be considered when designing the active region of green LDs[15-16]. To achieve lasing in the green region (around 520 nm), the MQWs should exhibit spontaneous emissions longer than 540 nm. (3) Incorporating a relatively high indium content requires a low growth temperature, which in turn increases non-radiative recombination defects such as impurity incorporation, point defects, and V-pits[17-19]. (4) As the wavelength increases, indium segregation becomes more severe, which reduces the thermal decomposition temperature of InGaN and facilitates the formation of dark spots during p-type layer growth[20].

The optimal growth temperatures of $In_{0.3}Ga_{0.7}N$ and GaN differ significantly, so a two-temperature growth method is commonly employed to epitaxially grow the $In_{0.3}Ga_{0.7}N$/GaN MQWs. However, indium is easy to desorb at high temperatures. Therefore, a cap layer is often deposited to suppress indium desorption during the two-temperature growth of the active region. AlN has a large bond energy (2.88 eV) and is thermally stable at high temperatures. Therefore, AlGaN can be employed as a protective layer to inhibit indium desorption from InGaN QWs and form sharper heterointerfaces[21-25]. AlGaN as an interlayer (IL) in LEDs or MQWs grown on sapphire substrates has been studied. It is found that the AlGaN IL can play a role in reducing the strain relaxation of MQWs[26-28]. It has also been reported that the AlGaN IL increases the polarization electric field in MQWs or leads to an increase in device voltage[23,28-29]. Other structures such as AlN/AlGaN QBs and AlInN ILs have also been adopted to enhance PL intensity[30-31]. AlGaN cap layers have been widely used in LEDs and MQWs fabricated on sapphire substrates. However, there are only a few reports on their application to green LDs grown on GaN substrates. In this work, an AlGaN cap layer is introduced into the active re-

gion. We investigated the morphology of the AlGaN cap layer, as well as its effects on the surface morphology of yellow- emitting MQWs. Finally, we fabricated InGaN/AlGaN/GaN MQW green LDs.

2 Experiment, Result and Discussion

All samples were grown by metal organic chemical vapor deposition (MOCVD) reactor. Both single quantum well (SQW) and MQW samples were grown on GaN/sapphire templates, while LD samples were grown on free-standing GaN substrates. The threading dislocation density (TDD) of the GaN/sapphire template is around 2×10^{8} cm^{-2}, and it is under compressive strain. Trimethylindium (TMIn), trimethylaluminum (TMAl), and ammonia (NH_3) were used as precursors for In, Al, and N, respectively. Triethylgallium (TEGa) and trimethylgallium (TMGa) were used as precursors for Ga. TMGa is used for high-temperature GaN growth, while TEGa is chosen for the growth of InGaN. Monosilane (SiH_4) and bis (cyclopentadienyl) magnesium (Cp_2Mg) were used as n- and p-type dopants, respectively. In addition, nitrogen and hydrogen were used as carrier gases. In MQWs, the QW and QB are grown at 840 °C and 1063 °C with growth durations of 78 s and 80 s, respectively. All temperatures mentioned above correspond to thermocouple temperatures. The indium composition of both the SQW and MQW samples is 30%. The aluminum composition of the AlGaN cap layer is 10%. The growth schematic of MQWs with an AlGaN cap layer is shown in Fig. 1.

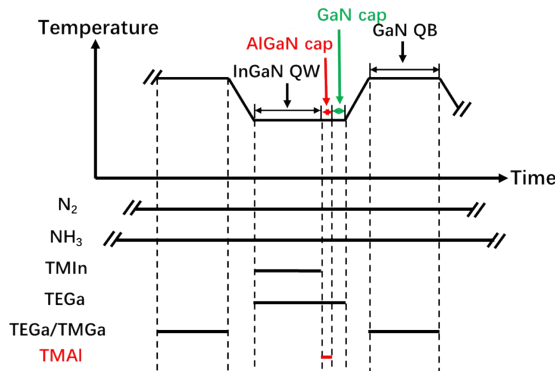

Fig.1 Schematic diagram of the growth process of InGaN/AlGaN/GaN MQWs.

2.1 SQW

The layer structure of SQW samples with different cap layers are shown in Fig. 2. The cap layers of the four SQW samples are 1 nm GaN, 1 nm AlGaN, 3 nm GaN and "1 nm AlGaN + 2 nm GaN" respectively.

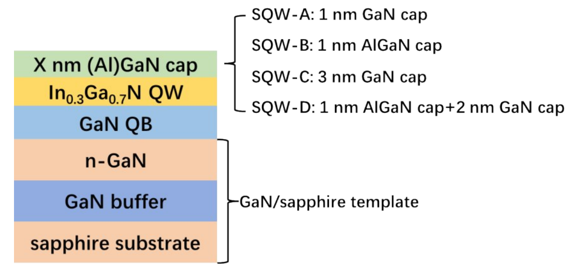

Fig.2 Schematic diagram of the SQW sample structures.

AFM images of the SQW samples are shown in Fig. 3. As shown in Fig. 3(a), the step-flow morphology appears in SQW-A, but the steps are discontinuous with rough edges and don't completely cover the underlying InGaN. When the thickness of the low-temperature GaN cap layer is increased to 3 nm, corresponding to sample SQW-C, its surface morphology is shown in Fig. 3(c). It can be observed that a smooth step-flow morphology has formed on the sample surface, with continuous steps and distinct step edges. However, trench defects with a density of 9×10^{7} cm^{-2} also appear on the surface simultaneously, which is detrimental to device performance. By comparing the two samples, it can be confirmed that trench defects form during the growth of the GaN cap layer. The AFM image of SQW-B is shown in Fig. 3(b). It can be seen that the AlGaN exhibits an island-like morphology. This is attributed to the low growth temperature of the AlGaN cap layer, resulting in insufficient migration mobility of Al atoms. As shown in Fig. 3(d), the trench defect density of SQW-D is 1.6×10^{8} cm^{-2}, which is significantly higher than that of SQW-C. It can be concluded that the AlGaN cap layer leads to an increasing trench defect density in the subsequently grown GaN layer. It has been reported in the literature that trench defects are induced by the In-rich surface of InGaN QWs[32]. These results indicate that the AlGaN cap layer inhibits Indium desorption from the

surface of InGaN QW. Thermal annealing and hydrogen treatment are commonly used to eliminate In-rich clusters[33-36]. In the following work, we introduced hydrogen during the growth of QBs to eliminate trench defects in MQW samples and LD structures.

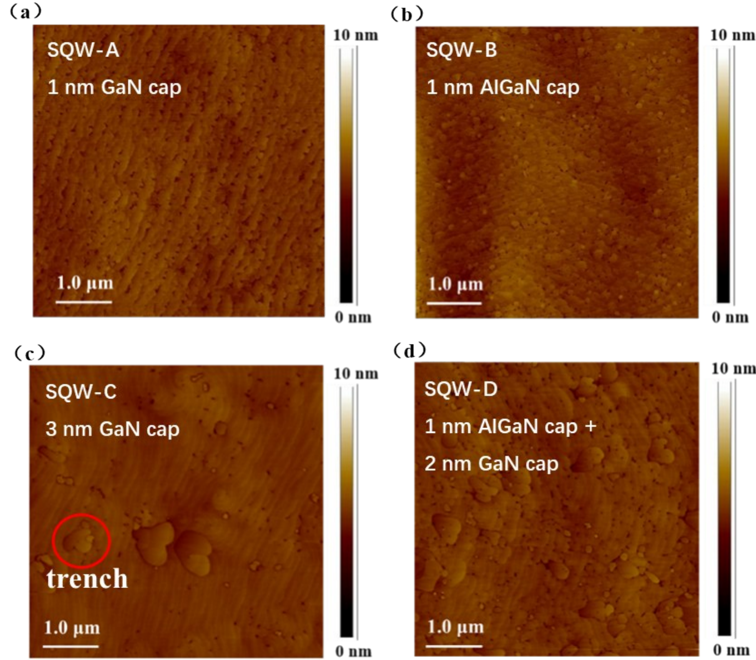

Fig.3 AFM images of SQW samples with different cap layers: (a) 1 nm GaN cap; (b) 1 nm AlGaN cap; (c) 3 nm GaN cap; (d) 1 nm AlGaN cap + 2 nm GaN cap.

2.2 MQWs

We then investigate the effect of AlGaN cap layers with different thicknesses on the surface morphology of InGaN/GaN MQWs. The MQW sample structures are shown in Fig. 4, and the thicknesses of the AlGaN cap layers are 0 nm, 0.5 nm, 0.7 nm, and 1 nm, respectively.

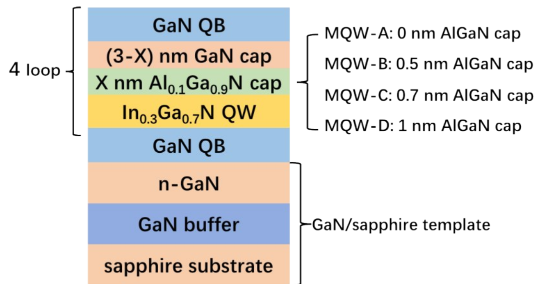

Fig.4 Schematic diagram of MQW structures with different thicknesses of AlGaN cap layer.

Fig. 5 shows the AFM images of the four MQW samples. The wavelengths of the four MQWs samples are 565 nm, 560 nm, 558 nm, and 569 nm, respectively. The AFM image of sample MQW-A with a GaN cap layer is shown in Fig. 5(a). Large V-pits are observed on the surface of sample MQW-A, and its root-mean-square (RMS) roughness is 0.85 nm. This is because the InGaN QWs and GaN cap layer partially decompose during the temperature ramping process for GaN QB growth, leading to the formation of V-pits on the sample surface. After introducing an AlGaN cap layer, the size of V-pits at the sample surface is significantly reduced, as shown in Fig. 5 (b)-(d). The RMS roughness values of MQW-B, MQW-C, and MQW-D are 0.74 nm, 0.49 nm, and 0.51 nm, respectively. The dependence of the RMS roughness on the AlGaN cap layer thickness is plotted in Fig. 6. By using an AlGaN cap layer, a yellow-emitting MQW active region with a roughness as low as 0.5 nm has been obtained. This is attributed to the high bond energy of Al-N, which makes AlGaN thermally stable and difficult to decompose. Consequently, it effectively protects the InGaN QWs, suppresses the formation of V-pits, and reduces the roughness of the yellow-emitting MQWs.

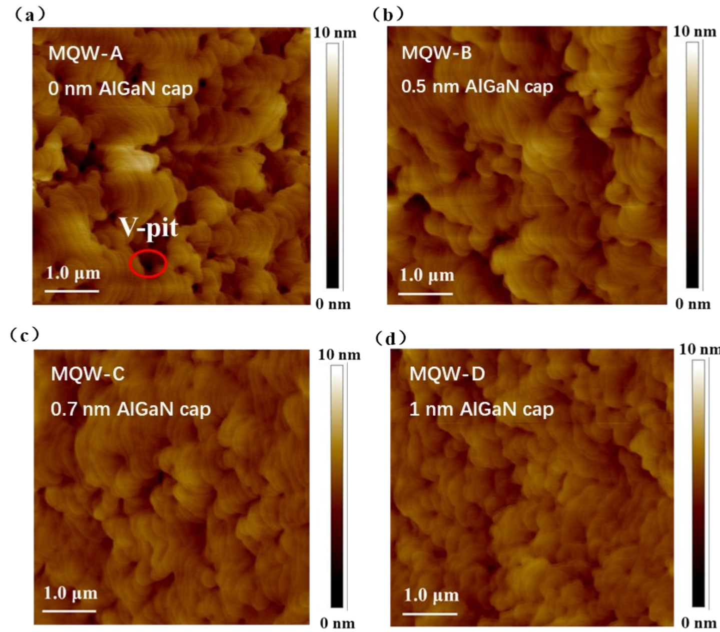

Fig.5 AFM images of yellow-emitting MQWs with different AlGaN cap layer thicknesses: (a) 0 nm AlGaN cap, (b) 0.5 nm AlGaN cap, (c) 0.7 nm AlGaN cap, (d) 1 nm AlGaN cap.

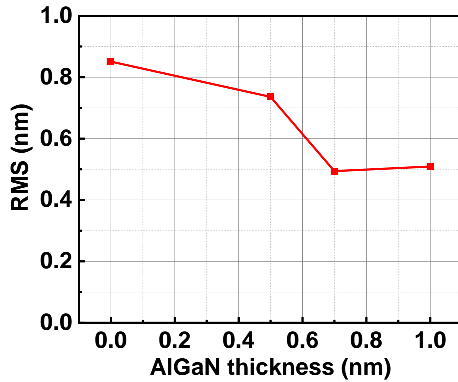

Fig.6 Dependence of RMS roughness of yellow-emitting MQWs on AlGaN cap layer thickness.

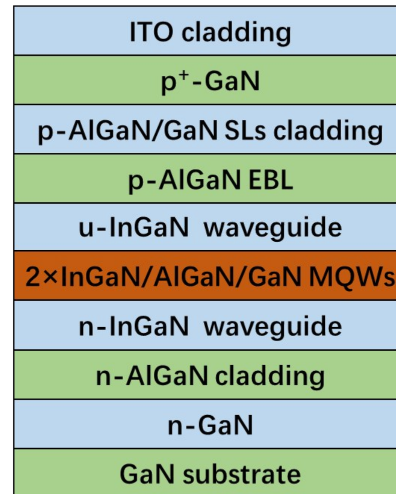

Fig. 7 Schematic structure of green LD grown on GaN substrate.

2.3 LDs

We then fabricated green LDs grown on GaN substrate with InGaN/AlGaN/GaN MQW active region. The structure of LD grown on GaN substrate is shown in Fig. 7. The thickness of the AlGaN cap in the MQWs is 0.5 nm, and the aluminum composition is 10%. The wafer was fabricated into ridge waveguide LD chips with ridge width of 15 μm and a cavity length of 1200 μm. The measurements of the LDs were carried out under pulsed operation at room temperature with a pulse width of 1 μs and a repetition frequency of 10 kHz. The results of the green LD are shown in Fig. 8. Fig. 8(a) shows the electroluminescence (EL) spectra of green LD at different current densities. At low current density (0.017 kA/cm^2), the spontaneous emission wavelength is 561 nm, and the full width at half maximum (FWHM) is 35 nm (138 meV). The narrow FWHM indicates the high crystalline quality of the active region[16]. As the carrier density of the LD increases, the emission peak exhibits a blue shift due to band filling and the screening of the polarization electric field[37]. At the current density of 8.3 kA/cm^2, the lasing wavelength is 520 nm. Fig. 8(b) and 8(c) show the power-cur-

rent(P-I) and current-voltage (I-V) curve, respectively. The slope efficiency is 0.36 W/A. At an operating current of 0.72 A (4 kA/cm^2), the operating voltage is 5.6 V. The output power is 180 mW at 2 A.

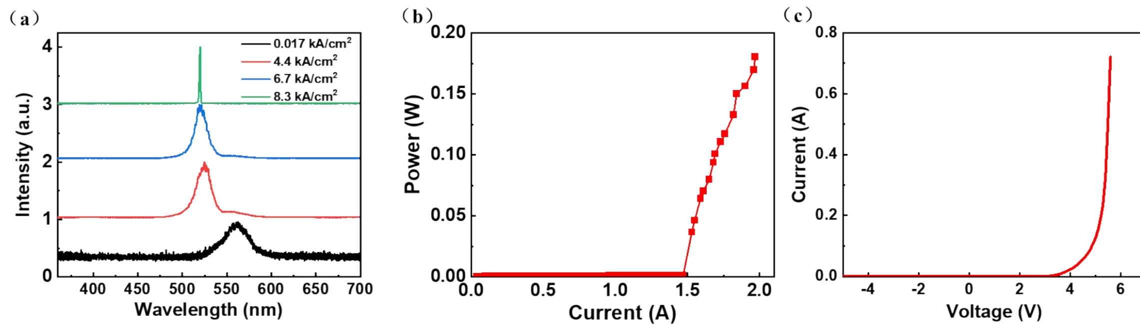

Fig.8 (a) EL spectra of green LD at different current densities, (b) Power-current (P-I) curve, and (c) Current-voltage (I-V) curve of InGaN/AlGaN/GaN QW green LD.

3 Conclusion

We have investigated the morphology of the AlGaN cap layer and its influence on the surface morphology of InGaN/AlGaN/GaN yellow-emitting MQWs. It is found that the AlGaN layer exhibits a two-dimensional island morphology, which is attributed to the low diffusion mobility of Al atoms at low temperature. Furthermore, owing to the protective effect of the AlGaN cap layer, the decomposition of the InGaN QW and the cap layer during thermal annealing is effectively suppressed. The size of V-pits is significantly reduced, yielding a yellow-emitting InGaN/GaN MQWs active region with a roughness as low as 0.5 nm. We also fabricated green LDs with InGaN/AlGaN/GaN MQW with a lasing wavelength of 520 nm. The LD exhibited a slope efficiency of 0.36 W/A and an output power of 180 mW at 2 A.

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